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THE EARLY CHRONOLOGY OF THE SOLAR SYSTEM

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A. G. W. Cameron

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SUMMARY

The solar system's early history can be deduced from a study of anomalies in the isotopic composition of certain elements extracted from meteorites. In stone meteorites, xenon is sometimes enriched in Xe^{129}; and in iron meteorites, silver is sometimes enriched in Ag^{107}. If these anomalies are attributed to the decay of the extinct radioactivities of I^{129} and Pd^{107}, then it is possible to deduce the approximate time intervals between the cessation of nucleosynthesis in the interstellar gas, and the formation and cooling of the meteorite parent bodies to the point where further fractionation of the elements involved ceases. This time interval is about 1.5×10^8 years for the xenon anomaly and about 2 to 4×10^7 years for the silver anomaly. The earth's atmosphere contains xenon that has been subjected to additional enrichment processes; the earth apparently did not start retaining any xenon until about 10^8 years following the retention of xenon by the meteorites.

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INTRODUCTION

One of the principal scientific objectives of the space program is the exploration of the moon and planets, and one of the principal goals of such exploration will be a determination of these bodies' histories. Many highly refined techniques will undoubtedly be used in the exploration program; among these will be the radioactive dating of certain events in the early history of the moon and planets. This can be done by studying anomalies in the isotopic composition of certain elements produced by the decay of extinct radioactivities. It is the purpose of this report to show how such anomalies, applied to a study of meteorites, are already giving information about the solar system's early history.

EXTINCT RADIOACTIVITIES

The first evidence for an effect due to an extinct radioactivity was obtained by Reynolds (Reference 1) at the end of 1959. He found that xenon gas extracted from certain stone meteorites had large excess abundances of the isotope Xe^{129}. The excess abundance of this isotope is attributed to the decay of the extinct radioactivity of I^{129}, which has a half-life of 1.7×10^7 years. A measurable amount of Xe^{129} must have been present at the time the meteorite parent body was formed, but it would have decayed shortly thereafter.

Actually, this anomaly in the isotope Xe^{129} is only one of many that have since been discovered in xenon extracted from various sources. Perhaps we should regard primordial xenon to be that which is extracted from bodies having the greatest amount of xenon per gram of material present. On this basis, the meteorites in general have much more xenon per gram than does the earth in its atmosphere; and certain of the stone meteorites, called carbonaceous chondrites, contain much more xenon than do most ordinary stone

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meteorites. Therefore, we might expect the xenon in the carbonaceous chondrites to resemble primordial xenon most closely.

The isotopic composition of xenon extracted from three carbonaceous chondrites (all of the measurements privately communicated from Reynolds) is shown in Figure 1. The histogram at the bottom of the figure shows the abundances of the various isotopes of xenon in the Murray carbonaceous chondrite, relative to Xe^{128}. The top part of the figure shows the differences between the xenon composition in two other carbonaceous chondrites (the Mighei and the Orgueil meteorites) and that of the Murray meteorite (regarded as a standard), expanded by a factor of ten. It may be seen that there is no essential difference between the composition of xenon in these meteorites, with the possible exception of slight differences in Xe^{129}. This constancy supports our use of the Murray meteorite composition as a primordial standard.

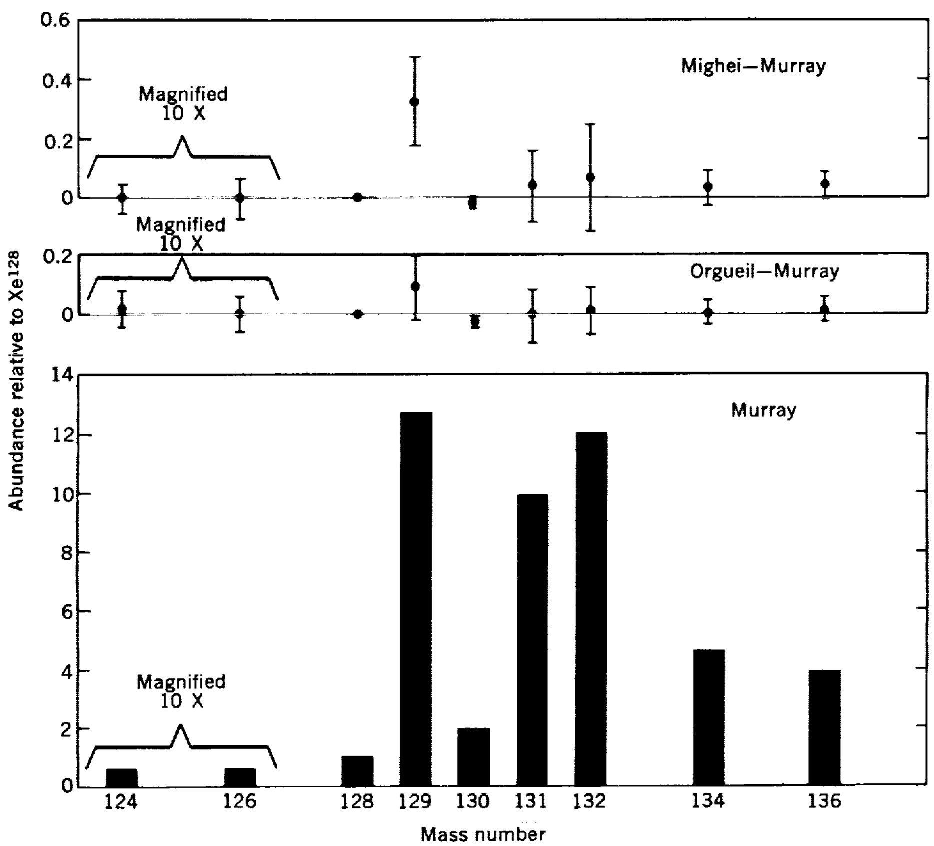

Figure 1—Comparison of the isotopic compositions of xenon extracted from three carbonaceous chondrites. To show the differences clearly, the ordinate scales of the upper plots have been enlarged by a factor of 10

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Figure 2 shows the difference between the isotopic composition of xenon extracted from a more ordinary chondritic stone meteorite (the Richardton meteorite) and from the Murray standard, which is again shown at the bottom of the figure. In this case, the ordinate has *not* been expanded by a factor of ten. There is no essential difference between the relative isotopic compositions of the Richardton and Murray meteorites, with the exception of Xe^{129}, which is seen to be greatly overabundant in the Richardton meteorite. Many other examples are now known in which a similar overabundance of Xe^{129} occurs. As was indicated earlier, this overabundance is attributed to the effects of the incorporation of some I^{129} in the meteorite parent body. Because xenon is a volatile element, there is a large fractionation between the abundances of iodine and xenon; therefore, only a small amount of I^{129} need be incorporated in the meteorite parent body in order to show up as an isotopic anomaly in the xenon daughter element.

When we turn to the body having the least fractional weight of xenon—the earth, including its atmosphere—we find an entirely different situation. The comparison between

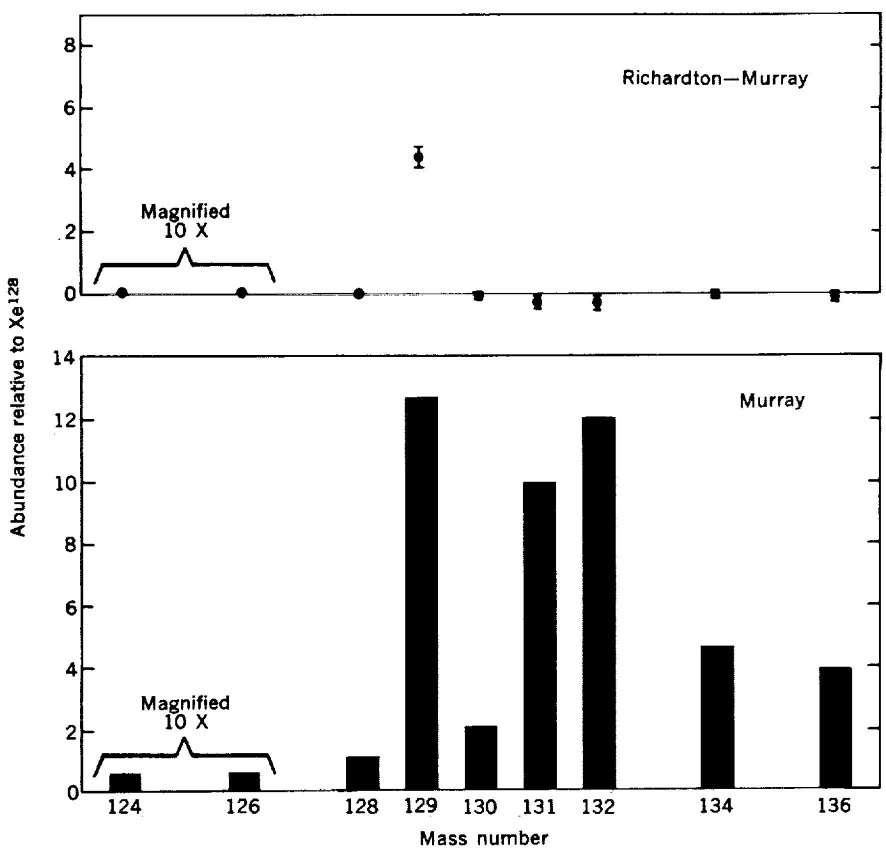

Figure 2—Comparison of the isotopic compositions of xenon in the Richardton and Murray chondrites

the composition of xenon in the earth's atmosphere and that of the Murray standard is shown in Figure 3. It may be seen that Xe^{129} is overabundant in the earth's atmosphere, but not by a large amount in comparison with similar overabundances of Xe^{131}, Xe^{132}, Xe^{134}, and Xe^{136}. It may also be seen that there are smaller but nevertheless real abundance differences in the lighter isotopes Xe^{124}, Xe^{126}, and Xe^{130}. This comparison has been made by normalizing on the isotope Xe^{128}; however it is likely that there is an anomaly in Xe^{128} comparable to that in Xe^{130}.

The isotopes shown in Figure 3 with large overabundances in the atmosphere (Xe^{129}, Xe^{131}, Xe^{132}, Xe^{134}, and Xe^{136}) are precisely those isotopes of xenon that can be formed from the beta decay of fission products. This suggests that some of the xenon in the earth's atmosphere is fissiogenic in origin. However, the amount of this fissiogenic xenon in the earth's atmosphere is much greater than can be expected from the spontaneous fission of

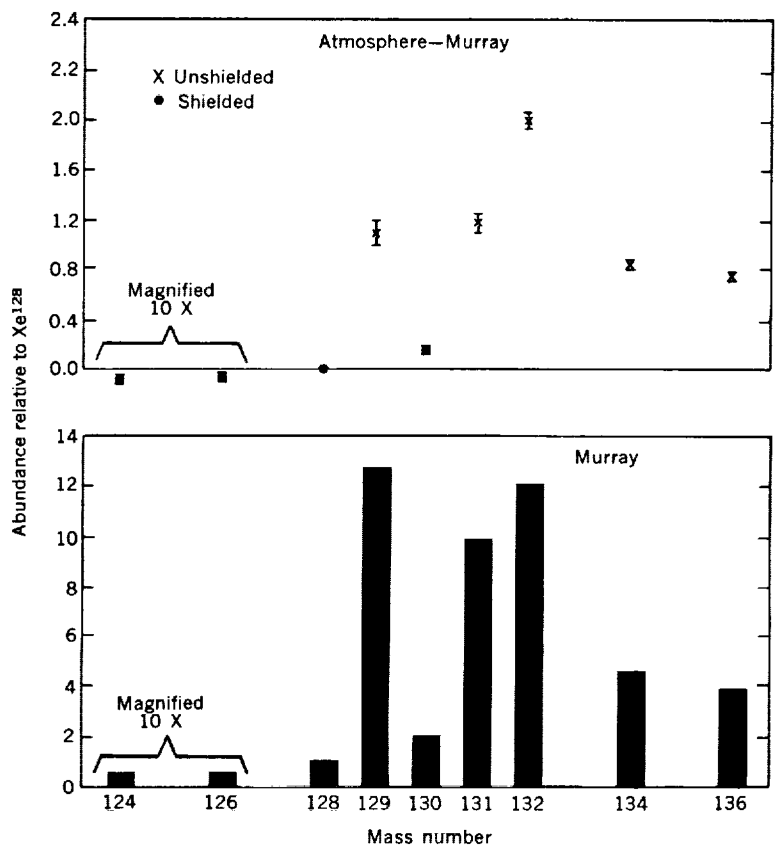

Figure 3—Comparison of the isotopic compositions of xenon in the terrestrial atmosphere and in the Murray carbonaceous chondrite. Those isotopes that can be formed by the β decay of fission fragments are denoted by crosses and labeled "unshielded." Those that cannot be so formed are the "shielded" isotopes denoted by solid circles. To show the differences clearly, the ordinate scale of the upper plot has been enlarged by a factor of 5.

uranium and thorium isotopes or from the neutron-induced fission of U^{235}. Also, the mass-yield curves of these types of fission do not agree with the overabundance pattern shown in Figure 3. Kuroda (Reference 2) has suggested that the extinct radioactivity of Pu^{244} has been responsible for the production of these fission products. The isotope Pu^{244} has a half-life of 7.6×10^7 years, and we must suppose that some of it was present in the earth at the time the earth was formed. However, since Pu^{244} should also have been present in the meteorite parent bodies when they were formed, and because the xenon extracted from meteorites does not show the presence of these fission products, we must ask why the earth does not contain a very much larger overabundance of Xe^{129} than is seen to be the case. Because there is so much less xenon per gram of earth than per gram of meteorite, we might expect the major part of the xenon in the earth's atmosphere to be Xe^{129}. Since this is not the case, it seems necessary to conclude that the earth did not retain xenon in its atmosphere for some considerable time after xenon was retained in the meteorite parent bodies.

It does not seem possible to explain the small anomalies (Figure 3) in the relative abundances of Xe^{124}, Xe^{126}, Xe^{128}, and Xe^{130} as resulting from the effects of extinct radioactivities. This pattern of anomaly can, however, be produced if xenon is subjected to a large flux of neutrons in the presence of comparable amounts of neighboring elements. This exposure may have occurred during the early history of the sun, when it was contracting from the interstellar medium, and when its deuterium was consumed in thermonuclear reactions. Some of the deuterium thermonuclear reactions produce neutrons, and the capture of these can produce small changes in the isotopic composition of the heavier elements. It seems reasonable to estimate that about 30 percent of the atmospheric xenon was once in the sun where it was subjected to a large neutron flux presumably accompanying deuterium burning. Perhaps this xenon has been subsequently captured into the earth's atmosphere from the solar wind.

Effects due to one other extinct radioactivity have been discovered by Murthy (Reference 3), who examined the isotopic composition of silver extracted from various phases of iron meteorites. Silver contains two stable isotopes of comparable abundance: Ag^{107} and Ag^{109}. Murthy discovered that the Ag^{107} in iron meteorites was enriched relative to Ag^{109} by amounts of the order of 2 to 4 percent. It happens that Ag^{107} is the daughter product of the decay of Pd^{107}, which has a half-life of 7×10^6 years. It also happens that the abundance of silver in iron meteorites is very low, while that of palladium is relatively high. Hence, if the meteorite parent body is formed with appreciable amounts of Pd^{107}, this can produce an enrichment of Ag^{107} under conditions in which silver is greatly fractionated relative to palladium, as in iron meteorites.

NUCLEOSYNTHESIS AND GALACTIC HISTORY

These radioactivities give us clues about the early chronology of the solar system. However, in order to make a proper interpretation of these extinct radioactive effects, we must also learn a great deal about the galaxy's history preceding the formation of the solar system. Current determinations of the ages of old galactic star clusters indicate that the galaxy is probably about three times as old as the solar system, which itself is about 4.5×10^9 years old. The oldest stars contain a much smaller ratio of heavy elements to hydrogen than do the sun and the newly formed stars. Hence, we believe that the galaxy was once nearly pure hydrogen gas. As the galaxy developed, stars were formed, and the more massive ones evolved quite quickly. The nuclear reaction products that were produced during this evolution were then thrown forth into the interstellar medium by supernova explosions, thus gradually building up a larger abundance of the heavier elements in this medium. Because this is a gradual process, radioactivities with half-lives of a few millions or tens of millions of years can be expected to be present in the interstellar medium to a small extent at any given time. It is the task of astrophysicists and nuclear physicists to determine what the appropriate model of element formation during galactic history has been, and thereby determine the level of abundances of these radioactivities in the interstellar medium at any time.

At some point, the solar system will start to condense out of the interstellar medium, probably as part of the formation of a cluster or association of stars. Once this contraction has started, we may expect that the solar system material will be isolated from the injection of any further radioactivities due to supernova explosions in nearby space. Hence, the existing level of the extinct radioactivities will start dying away. If we can estimate the abundance level in the interstellar medium before a contraction started, and if we can also measure the abundance level of the extinct radioactives in various chemical systems at the time chemical fractionation ceases, then we can determine the time, relative to the start of the contraction, at which the final chemical fractionations occur. In this way we should be able to determine, from the anomalous silver content of the iron meteorites, the time from the start of the contraction through the collection, thermal insulation, and heating of the meteorite parent bodies and their cooling to the point where iron solidifies. From the amounts of anomalous Xe^{129} trapped in the stone meteorites, we can determine the time interval from the start of the contraction through the heating and cooling of the meteorite parent bodies to the point (about 200°K) where xenon can no longer diffuse through them. We can similarly date the retention of xenon in the earth's atmosphere.

These time-interval estimates have been made on the basis of the model of galactic history shown in Figure 4. The philosophy behind the construction of this history is as follows. If we expect that the galaxy was once composed entirely of gas, then star formation would occur much more rapidly than it does at present. We therefore assume that star formation falls off exponentially with time from the beginning of galactic history (taken to be about 1.5×10^{10} years ago). A study of the nuclear reactions responsible for element formation leads to a classification of the elements into two groups. First, there are the elements that can be formed directly by a sequence of nuclear reactions starting from a pure hydrogen gas; these include all the abundant light and medium-weight elements through

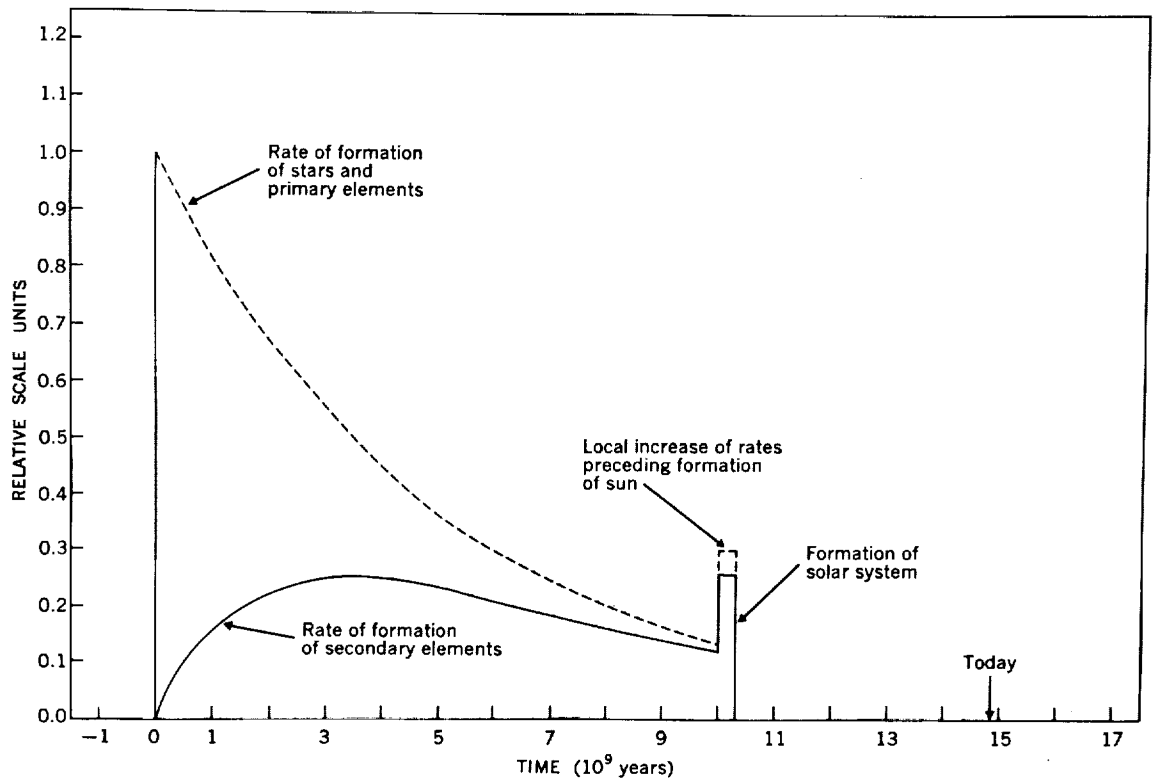

Figure 4—The model of galactic history used for calculating the abundances of radioactive nuclei in the interstellar medium at the start of the condensation that forms the solar system

iron, and are called the *primary* elements. Secondly, there are the elements that can only be built from the primary elements; these are called the *secondary* elements, and include all the extinct radioactives. It is assumed in the model shown in Figure 4 that the formation of primary elements occurs at the same rate as star formation, and the secondary elements are formed at this rate multiplied by the fractional build-up of the primary elements toward their saturation level. The rate of falloff of the primary element production was determined in Figure 4 from the relative abundances of Th^{232} and U^{238}, for the assumed galactic age.

Many different kinds of observations show that star formation is strongly concentrated toward the spiral arms of our galaxy and, in particular, that it is associated with the very dense clouds of gas and dust that can be found in such spiral arms. Stars appear to be continually forming in such regions, and those that evolve rapidly and produce supernova explosions will contribute fresh radioactivities, especially to this region where star formation is going on. Furthermore, the observations suggest that the gas in the plane of the galaxy is streaming radially outwards at a rate that amounts to some 50 km/sec at about

3 kiloparsecs from the galactic center, and at a rate of the order of 8 km/sec at the distance of the sun from the galactic center (about 8 kiloparsecs); the gas will take about 3×10^8 years to traverse this distance.

These observations thus suggest that the gas that is going to form fresh stars is locally enriched in fresh radioactives. This accounts for the feature shown in Figure 4 as the local production of elements immediately prior to the formation of the solar system. The length of time assumed for this local production is 3×10^8 years, and the increased rate of the production was determined from the ratio of U^{235} to U^{238} in the solar system. We assume that, following this increased local rate of element production, condensation started and there was no further contribution of fresh radioactivities to the material contracting to form the solar system. There is then an unknown but, as we shall see, fairly short interval of time required for the condensing material to get into the form of solid bodies circling about the sun. We know from the variations in the relative abundances of the lead isotopes in the earth and in the meteorites that 4.5×10^9 years has elapsed since uranium was chemically isolated from lead in such bodies.

EARLY CHRONOLOGY OF THE SOLAR SYSTEM

The chronology of the events that can thus be deduced for the solar system's early history is shown in Figure 5. The time intervals shown in this figure have been calculated

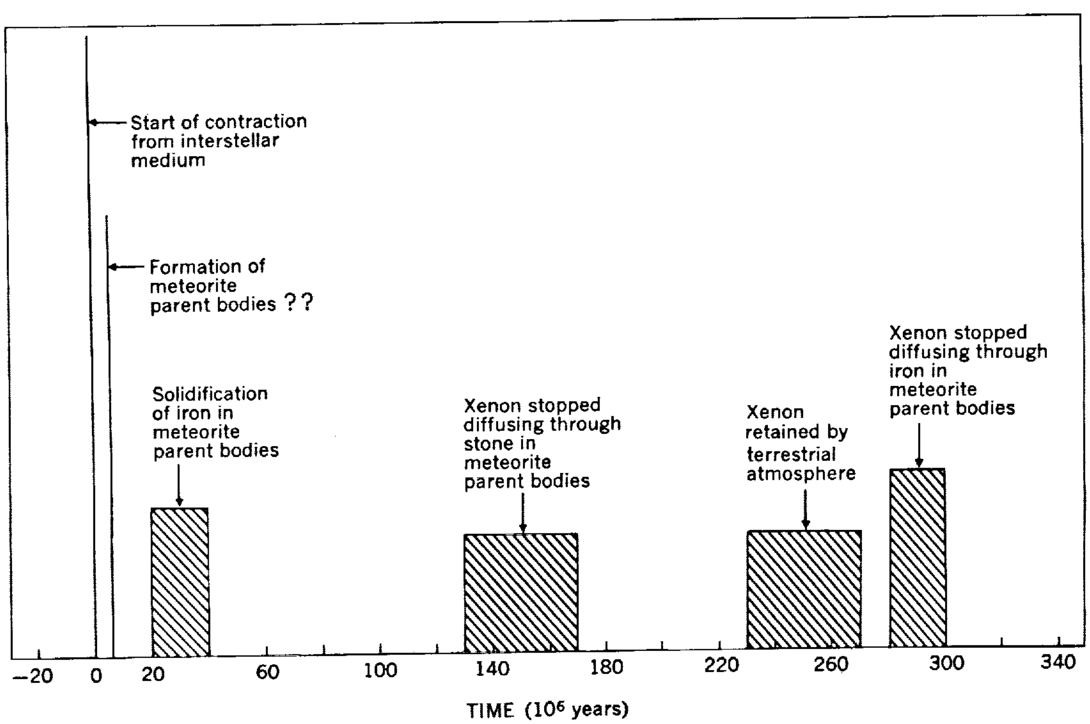

Figure 5—The early chronology of the solar system as deduced from the abundances of the decay products of extinct radioactivities in various systems

for the abundances of fresh radioactivity in the interstellar medium corresponding to the model of galactic history shown in Figure 4; the ends of these intervals are deduced from the levels to which the radioactivity has fallen at the time when chemical isolation of the appropriate system has occurred.

The first interval shown in Figure 5 has not been deduced from any existing evidence for an extinct radioactivity, but is a possibility corresponding to one hypothesis concerning the heating of the meteorite parent bodies. It is rather difficult to see where the heat necessary to melt iron in such meteorite parent bodies could have arisen, since the evidence indicates that the bodies cooled quickly and were therefore rather small. The gravitational potential energy is much less than that required to provide the necessary heating. Fish, Goles, and Anders (Reference 4) have suggested that the extinct radioactivity of Al^{26} was responsible for this heating. If that is the case, we can set a lower limit to the amount of Al^{26} that must have been present at the time the meteorite parent bodies were collected together and became thermally insulated. The resulting time interval from the start of the contraction to the thermal insulation of the meteorite parent bodies turns out to be less than 6×10^6 years. This is a rather short time for the formation of the solar system by contraction out of the interstellar medium, but it seems by no means to be excluded. However, it must be emphasized that we are not restricted to this time interval if another explanation can be found for the heating of the meteorite parent bodies.

The next interval determined by the extinct radioactivities is that associated with the cooling of the meteorite parent bodies to the point where iron solidifies. This is determined from the anomalous abundances of the isotope Ag^{107} in iron meteorites. Because there is as yet no good determination of the anomalous abundance of Ag^{107} and of the abundance of palladium in the same meteorite samples, we must use average values for such abundances. This leads to a spread in the derived ages associated with the uncertainty in the silver-to-palladium ratio. The resulting time interval turns out to be 2 to 4×10^7 years.

The remaining time intervals shown in Figure 5 have been derived from the evidence concerning the anomalous abundances of Xe^{129}. The stone meteorites appear to have solidified and cooled to the point (approximately 200°K) where xenon can no longer diffuse through them in a time of the order of 1.5×10^8 years following the start of the contraction from the interstellar medium. Somewhat different results are obtained for different samples, as might be expected, since different places in the meteorite parent bodies may have cooled to a sufficiently low temperature at different times.

We have already discussed the evidence indicating that the earth did not retain xenon in its atmosphere for some considerable time after the meteorite parent bodies cooled to this low temperature. From the overabundance of Xe^{129} in the atmosphere, it can be estimated that the time interval associated with the retention of xenon in the atmosphere seems to be of the order of 10^8 years longer than that associated with the retention of xenon in the stone meteorites. In principle, we can obtain a similar estimate of the time at which the earth started retaining its xenon, from the abundances of the xenon fission products from the decay of Pu^{244}. Because of the various uncertainties involved, this time is not very well determined; but it is quite consistent with the interval shown in Figure 5.

Reynolds, Merrihue, and Pepin (Reference 5) found primordial xenon in the iron meteorite Sardis. This has an anomalous abundance of Xe^{129}. The evidence shows that xenon was able to diffuse out of this iron component of the meteorite parent bodies until a time slightly greater than that at which the earth started retaining xenon in its atmosphere. It is perhaps not too surprising that this turns out to be considerably greater than the time at which the stone parts of the meteorite parent bodies cooled sufficiently to retain xenon, since the iron component of the meteorite parent bodies has obviously been heated much more than the stone component.

These results show the great power of the radioactive dating method in casting light on the sequence of events in the solar system's early history. It will be very interesting to determine the isotopic composition of xenon in the atmospheres of the planets and of the moon (if the latter's atmosphere contains any xenon), and hence to determine the dates at which such atmospheres have started to retain some xenon. We shall also be interested in learning whether the xenon in the rocks of the moon, the planets, and the asteroids contains xenon of abnormal composition, which would allow the thermal history of such bodies to be determined. This indicates one very desirable direction in which future experiments in space research can be designed. At the same time, we have seen how much the proper interpretation of these results depends upon a knowledge of the preceding history of the galaxy. This illustrates the importance of an interdisciplinary approach in space science, and shows the need for vigorous investigations in many branches of astrophysics at the same time the exploration of the moon and planets is being carried out.

The analyses and results summarized in this paper are published in more detail elsewhere (Reference 6).

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